# Linear and nonlinear coupling of quantum dots in microcavities

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**Abstract.** We discuss the topical and fundamental problem of strong-coupling between a quantum dot an the single mode of a microcavity. We report seminal quantitative descriptions of experimental data, both in the linear and in the nonlinear regimes, based on a theoretical model that includes pumping and quantum statistics.

## Introduction

After its pioneering observation in micropillars [1] and in photonic crystals [2] in 2004, strong-coupling of light and matter is now commonplace in zero-dimensional nanostructures [3, 4, 5, 6, 7, 8]. This physics is primordial both for fundamental research and technological applications, from thresholdless lasers and new light-sources to quantum information processing. We have given the first quantitative description of experimental data [9] (see Fig. 1), by providing a general model of quantum modes coupling [10]. Our model extends the atomistic description, that limits to the excited state of the atom in an empty cavity as an initial condition. In semiconductor microcavities, however, photoluminescence measurements are typically made in the steady state established by a continuous, incoherent pumping. We take these specificities into account and: i) recover the spontaneous emission case of an arbitrary initial state in the limit of vanishing pumping, thereby providing a complete, self-Consistent and general description of light-matter coupling, and ii) include dynamical effects of quantum statistics for non-vanishing pumping, such as Bose stimulation and Pauli blocking.

1. Linear regime

When pumping is very small, so that the system is most of the time in vacuum, and occasionally excited, its photoluminescence spectrum is that of spontaneous emission of the state that results from the averaged excitation. In a microcavity, excitation is typically sought to be of the quantum dot itself, by mean of electron-hole pairs relaxation from off-resonant pumping [11]. As such, its photoluminescence spectrum would recover that of the atomic literature [12], up to a technical correction that consists in computing the cavity mode spectrum (for a microcavity) rather than the direct atomic de-excitation (for an optical cavity). However, various mechanisms result in an effective microcavity pumping, where photons are directly injected into the coupled light-matter system. One vivid scenario is that the quantum dot of interest, in strong-coupling with the cavity, is a "lucky" one—well positioned in the optical field, with adequate coupling strength, etc.—but is surrounded by many other dots, less efficiently coupled to the cavity (in weak-coupling). These are also excited by electron-pairs ideally intended for the strongly-coupled dot only. The other dots can release efficiently (by Purcell enhancement) and with no correlations (in a Markovian approximation) their excitation in the cavity mode and as such bath the lightmatter system of interest in a photonic environment. As the initial state (and effective quantum steady state) affects

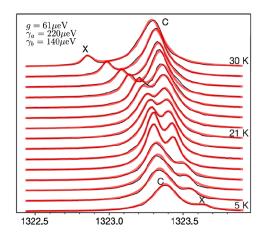


Fig. 1. Fit in the linear regime: data of Reithmaier et al. [1] with—superimposed in red—our global fit [9].

dramatically the spectral shapes, it is important to take into account both excitation channels to reproduce experimental data, in particular as effects of pumping are known to produce nontrivial phenomenology even at a qualitative level [13]. Most strikingly, at resonance, neither a doublet is a guarantee of strong-coupling nor a singlet is an evidence of weak-coupling. The analysis should be done at the level of spectral shapes rather than for the anticrossing of the maxima, for which there is no closed expression [14].

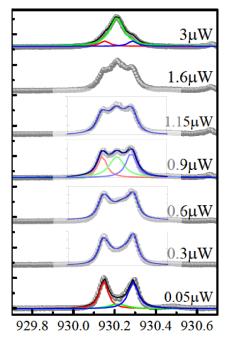
# 2. Nonlinear regime

When pumping is non-negligible, quantum statistics is to be added to the previous considerations. In the case of a large or elongated quantum-dot, where the electron and hole can bind as an exciton, the underlying statistics is that of Bose-Einstein [15]. This results in stimulated emission and line narrowing with increasing pumping (Schallow-Townes effect). If, on the other hand, the electron and hole are quantized separately in a small quantum dot, Pauli exclusion prevents other electrons and holes to populate the already excited dot, and the statistics of Fermi-Dirac rules the dynamics. As a conclusion, increasing excitation can lead to a variety of rich nonlinear effects, in the wake of Jaynes-Cummings physics (strong coupling of a boson and fermion). An important expected manifestation is full-field quantization, that results in a series of peaks at anharmonic frequencies  $\pm(\sqrt{n}\pm\sqrt{n-1})$  when n excitations are in the system [16]. State of the art technology does not yet allow to resolve clearly this fine-structure in semiconductors, although we find that a careful analysis in a situation with significant cavity pumping, could evidence manifestations of nonlinearities at the quantum level [17].

Another important expected manifestation of a two-level system brought in the nonlinear regime by high pumping is lasing. Recently, the transition from vacuum strongcoupling to lasing has indeed been reported [18]. In another, related work [19], this transition was observed to pass through a stage where a triplet is formed by appearance of a peak at the cavity mode frequency that subsequently overtakes the polariton modes as the system enters into lasing (see Fig. 2). Various explanations have been advanced for spectral triplets of this type [3, 19]. We offer one that, including a term of dephasing—which has been demonstrated to play a key role with increasing pumping [7]—explains the appearance of the triplet as a melting of the inner transitions between rungs of the Jaynes-Cummings ladder. Such a transition, if confirmed, would provide a striking crossover from the quantum realm, where single quanta rule the dynamics of the system [20], to the classical world, where a continuous field (the lasing mode) takes over a small number of quantum correlators. We have confronted our theory with the experimental data, again by fitting, but the situation in the nonlinear regime is significantly more complicated, owing to the lack of closed expressions for the spectral lineshapes. We have used genetic algorithm methods to do a global fitting of the data. We find our proposition to be consistent with the supposed parameters of this experiment, beside with a neat contribution due to a drift in detuning more than to dephasing. Beyond supporting claims of quantum nonlinearities, our work also provides the first quantitative description of strong-coupling experimental data but now in the nonlinear and fermionic regime.

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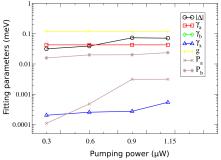


Fig. 2. Fit in the nonlinear regime: data of Ota *et al.* [19] with—superimposed in blue for the four central panels—our global fit (fitting parameters appear below) with a fermion model [17] including dephasing [21].

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